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Truetime Model GPS-DC-552 MK III GPS Receiver Live Static Test

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The GPS Program Offices, Los Angeles Air Force Base, California, has established a Center of Expertise (COE) comprised of several agencies, each providing unique GPS test capabilities for the purpose of developing a Commercial Receiver Test Program (CRTP). The Responsible Test Organization (RTO) for the COE is the 746th Test Group, 46th Guidance Test Squadron, Holloman, Air Force Base, New Mexico.

The Naval Research Laboratory (NRL) has been designed as a COE with the responsibility of testing the time output characteristics and accuracy of the commercial receivers. The NRL clock testing facility has time traceable to the U.S. Naval Observatory and the procedures used are taken from the CORE INS/GR/EGI TEST PLAN prepared by RTO.

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EXECUTIVE SUMMARY

The Global Positioning System (GPS) Joint Program Offices (JPO), Los Angeles Air Force Base, California, has established a Center of Expertise (COE) comprised of several agencies each providing unique GPS receiver test capabilities. The Responsible Test Organization (RTO) for the COE is the 746th Test Group, 46th Guidance Test Squadron, Holloman Air Force Base, New Mexico. The Naval Research Laboratory (NRL) has been designated as the Participating Test Organization (PTO) with the responsibility of testing the Precise Time and Time Interval (PTTI) characteristics of both commercial and military GPS receivers[1].

The Defense Information System Agency (DISA) operates several hundred communication sites throughout the world. These sites have a requirement for precision frequency standards. Loran-C frequency receivers have been used successfully for many years at these DISA communication sites. With the advent of GPS the U.S. Coast Guard discontinued its worldwide management of the Loran system. In 1992 the GPS JPO, acting as the Lead Military Department for procurement of the DISA receiver, selected Quantic Industries to deliver Precise Position Service (PPS) C/A code Timing GPS Receivers (TGR) to be used to replace the DISA Loran-C receivers. These receivers were originally scheduled to be delivered during the summer of 1993. In September 1994, because of the lengthy technical delays, DISA decided it could no longer wait for the Quantic GPS receivers. Instead they purchased and fielded 270 GPS receivers from Truetime, Inc.

Preliminary testing completed during the summer of 1994 on a standard commercial Truetime Inc. Model GPS-DC-MARK III receiver, found that this receiver would meet DISA's most critical frequency and time keeping requirements. The Truetime receiver used for this NRL evaluation was later upgraded to match the exact model receiver procured by DISA. This upgraded unit became a Model GPS-DC-552 MK III (MK III) receiver which is "XL based" and uses the SVEESIX Trimble front end. The test results in this report apply only to this model receiver. A series of long term time and frequency measurements were made over the next year to see how close the Truetime receiver came to meeting the original TGR specifications.

The Truetime MK III tested at NRL was found to meet most of the TGR time and frequency performance specifications. Its most glaring weakness comes from the fact that it is not a PPS GPS receiver. The MK III does not meet the TGR frequency stability specification at 100 and 1000 seconds because of the combination of SA and the frequency steering algorithm used.

The Truetime MK III one pulse per second time output was also found to be lagging GPS time by 76.1 ± 4.5 nanoseconds. The TGR specifications requires a 10 volts peak level for the one pulse per second signal whereas the MK III produced only a TTL pulse. The MK III phase noise floor was 6 dB above the TGR specification of -135 dBc.

TRUETIME MODEL GPS-DC-552 MK III GPS RECEIVER LIVE STATIC TEST

1. INTRODUCTION

The Global Positioning System (GPS) Joint Program Offices (JPO), Los Angeles Air Force Base, California, has established a Center of Expertise (COE) comprised of several agencies each providing unique GPS receiver test capabilities. The Responsible Test Organization (RTO) for the COE is the 746th Test Group, 46th Guidance Test Squadron, Holloman Air Force Base, New Mexico.

The Naval Research Laboratory (NRL) has been designated as the Participating Test Organization (PTO) with the responsibility of testing the Precise Time and Time Interval (PTTI) characteristics and accuracy of both commercial and military GPS receivers. NRL has a precision clock evaluation facility (PCEF) with time and frequency traceable to the U.S. Naval Observatory (USNO) Universal Time Coordinated (UTC). The test procedures used by NRL are taken from the COE's CORE Inertial Navigation System/GPS Receiver/Embedded GPS-INS (INS/GR/EGI) Test Plan[1] and from NRL's internal test plan[2] prepared as a COE member.

The Defense Information System Agency (DISA) operates several hundred communication sites throughout the world. These sites have a requirement for precision frequency standards. Loran-C frequency receivers have been used successfully for many years at these DISA communication sites. With the advent of GPS, the U.S. Coast Guard discontinued its worldwide management of the Loran system. In 1992 the GPS JPO, acting as the Lead Military Department for procurement of the DISA receiver, selected Quantic Industries to deliver Precise Position Service (PPS) C/A code Timing GPS Receivers (TGR) to be used to replace the DISA Loran-C receivers. These receivers were originally scheduled to be delivered during the summer of 1993. In September 1994, because of the lengthy technical delays, DISA decided it could no longer wait for the Quantic GPS receivers. They purchased and fielded 270 GPS receivers from Truetime, Inc. instead.

A Truetime Inc. Model GPS-DC-552 MK III (MK III) (SN#849) was tested at NRL to certify and validate the receiver's performance for use as an alternative to the Quantic TGR. Preliminary testing completed during the summer of 1994 found that the Truetime Inc. Model GPS-DC MARK III would meet DISA's most critical frequency and time keeping requirements. The test results here are for the "XL based" (using the SVEESIX Trimble front end) Model GPS-DC-522 MARK III (MK III) that was procured by DISA, and does not apply to other

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versions of the MK III receivers. A series of long term time and frequency measurements were made over the next year to see how close the Truetime unit came to meeting the original TGR specifications.

1.1 Test Item Description

The Truetime MK III GPS receiver is designed to provide precise time and frequency that is traceable to USNO. The MK III receiver uses the L1 (1575.42 Megahertz) Coarse Acquisition (C/A) code signal provided by the NAVSTAR GPS satellites. This MK III receiver is an off the shelf, commercial product, that was not designed for DOD military applications and is not PPS-Y code capable.

The MK III has been designed to be completely automatic in satellite signal acquisition. Whenever the site position information is not known to within the required accuracy of less than ±25 meters, it will be necessary to track four satellites to allow the MK III to determine its antenna position. From that point on, the MK III will require only one satellite to maintain valid time. However, operation to the specified frequency stability requires four or more satellites. When no satellites are in view, the MK III will continue to output its PTTI signals using the internal disciplined oscillator.

The Truetime MK III uses a Wenzel incorporated high quality ovenized voltage controlled crystal oscillator (VCXO) as an internal time base. This oscillator's frequency is steered to the received GPS timing signals. After considering the effects that room temperature changes could have on system performance, DISA requested that Truetime shorten its receiver's loop time constant to improve its response to temperature changes. Because of this change the short term frequency stability will be degraded. The MK III produces precise time in the form of an IRIG-B time code and a one pulse per second (PPS) signal which was not evauluated in this report. The MK III has three frequency outputs (1, 5 and 10 MHz). and has the ability to measure an external frequency source. A discrete fault indicator is included to let the user know if the receiver is operating normally. The interface layout can be seen in (figure C.1).

2. TEST OBJECTIVES

Evaluate the frequency and timing performance of Truetime Inc. Model GPS-DC-552 MK III receiver with respect to the vendor and TGR specifications. The specific test objectives are summarized below.

2.1 Performance Evaluation, Specifications, Test, And Document Paragraph Matrix

Table 1 provides a matrix of the paragraph numbers where the MK III performance specification, test description, test results and TGR performance specification can be found. A comparison of the TGR performance specifications and the performance specifications to the MK III test results are made in the test result paragraphs.

Test Objective: Evaluate	MMK III Performance Specification Paragraph	MK III Test Description Paragraph	MK III Test Result Paragraph	TGR Performance Specification Paragraph
Self Survey Accuracy	E.1	3.1	4.1	B.1
Timing Accuracy	E.2	3.2	4.2	B.2
One Pulse-Per-Sec Output	E.3	3.3	4.3	B.3
Spurious And Harmonic GPS Content	E.4	3.4	4.4	B.4
Phase Noise Measurements	E.5	3.5	4.5	B.5
Frequency Accuracy	E.6	3.6	4.6	B.6
Frequency Stability	E.7	3.7	4.7	B.7

Table 1. Matrix of Test Objectives Paragraph Numbers

3. TEST DESCRIPTIONS

The MK III receiver is not PPS capable so the errors induced by selective availability (SA) are not removed during these test. All tests were performed using reception from live operational satellites. Details of measurement methods and test equipment used are presented in Appendix A. Testing started during the summer of 1994 and was concluded in Jan 1996.

3.1 Position

The receiver's GPS antenna was placed near NRL's Defense Mapping Agency (DMA) benchmark on the roof of NRL building 53.

3.2 Time Accuracy

The Truetime MK III One Pulse Per Second (1PPS) timing output was measured against the NRL time scale. This time scale is traceable to USNO (UTC) to within a few nanoseconds.

3.3 1PPS Output

Pulse width, rise and fall times, peak voltage, and overall wave form of the 1PPS were displayed on a Giga-sample digital sampling storage oscilloscope and recorded.

3.4 Spurious And Harmonic Content

The 5 MHz sine wave output on the rear panel (see figure C.1) was checked for spurious and harmonic signals.

3.5 Phase Noise Measurements

The 5 MHz sine wave output on the rear panel (see figure C.1) was examined for phase noise and spurious content from DC to 100 KHz.

3.6 Frequency Accuracy

The absolute frequency offset of the 5 MHz sine wave output with respect to the NRL house frequency reference Hydrogen Maser was measured. The NRL maser frequency is then referenced to the USNO Master Clock.

3.7 Fractional Frequency Stability

Phase difference data between the NRL N1 Maser and the MK III 5 MHz sine wave output were recorded. This data was then used to calculate the frequency stability of the MK III in the form of the Allan Deviation.

4. TEST RESULTS

A brief synopsis of the results of the tests is presented in the following paragraphs. Detailed descriptions of the results as well as graphs of wave forms and measurements are provided in Appendix D.

4.1 Position

The Truetime MK III GPS antenna was installed on the roof of NRL building 53, at a Defense Mapping Agency (DMA) benchmark. Position coordinate errors are listed in table 2.

Dimension	Receiver derived position WGS-84	Receiver true position WGS-84	Error
height	-15 (m)	-16.15 m	-1.15 ±0.5 m
latitude	N 38° 49.2367′	N 38° 49.2363′	S 0.74 ±1.5 m
longitude	W 77° 01.465'	W 77° 01.4676'	W 3.75 ±1.2m

Table 2. Position Error Measurements

Receiver	Spherical Error, RSS	Specification
MK III	4.2 ± 2 m	< 10 m
TGR	3.1 m typical	< 5 m

Table 3. MK III receiver comparison with the TGR receiver specifications.

4.2 Timing Accuracy

A detailed calibration of all MK III timing system errors were completed. The MK III 1PPS time signal, when averaged over time intervals of 24 hours, and covering a period of three months was found to be lagging GPS time by 76.1 ±4.5 nanoseconds. A segment of this data is shown in figure D.1. The GPS scale is steered[6], as needed, on a daily basis to be within one microsecond of UTC(modulo one second). During long term testing it was found that the MK

III does makes the integer second correction to UTC but not the full correction epoch of GPS to UTC(USNO) corrections as specified in GPS ICD-200. This means that the time accuracy of the MK III with respect to UTC(USNO) can only be as good as GPS time.

4.3 One Pulse-Per-Second Output

The output 1PPS is a TTL-type logic level compatible, positive-going, 20 microsecond wide pulse when driving a 50 ohm load impedance. Table 4 contains a summary of these measurements. The full pulse is shown in figure D.2 with an amplitude of 3.4 volts with a slight overshoot. Figure D.3 shows that the MK III 1PPS timing signal has a very fast rise time of 1 nanosecond. The fall time is shown in figure D.4, also 1 nanosecond. Figure D.5 shows unwanted EMI leakage from the IRIG circuitry that bleeds into the 1PPS output.

	Amplitude	Rise time	Fall Time	Pulse Width
MK III Measured	3.4 V	1 ns	1 ns	20 us
TGR Specification	10 V ± 10 %	< 20 ns	< 1 us	20 us ± 5%

Table 4. Characteristics of the 1PPS

4.4 Spurious And Harmonic Content

The Truetime MK III primary frequency outputs have a signal level of + 13 dBm, figure D.6 shows the 5 MHz output and its harmonic content out to 50 MHz. Numerous unwanted frequency spurs can be seen in figures D.7 and D.8 but all are within specification. The summary of the test results are shown in table 5.

	Spurious 5 MHz	Harmonic 5 MHz
MK III Specification	Not Specified	-50 dBc
TGR Specification	-60 dBc @ 1 MHz	-40 dBc
MK III Measured	-78 dBc	-60.2 dBc, 1st Har

Table 5. Spurious And Harmonic Content

4.5 Phase Noise Measurements

The 5 MHz sine wave output on the rear panel was examined for phase noise and spurious content. The MK III receiver has a phase noise floor at -127 dBm with a number of spurs that can be seen in figures D.9 through D.12. The 1PPS timing signal is clearly shown bleeding over into the frequency outputs in figure D.9. A particularly large peak can be seen in figure D.12 at about 78 kHz, this may be due to the receivers switching power supply. General results are shown in table 6.

Frequency	10 Hz	100 Hz	10 KHz	100 KHz
MK III Specification	None	None	None	None
TGR Specification	-87 dBc/Hz	-120 dBc/Hz	-135 dBc/Hz	None
MK III Measured	-115.5 dBc/Hz	-114.3 dBc/Hz	-126 dBc/Hz	-127 dBc/Hz

Table 6. Phase Noise

4.6 Frequency Accuracy

The absolute frequency offset of the 5 MHz sine wave output with respect to USNO was measured. The data is shown in figure D.13 with the results shown in table 7. The MK III frequency measurement value is the result of data averaged from (10) 3 hour averaging periods per the TGR SCN-3 specifications.

	Specifications	Measured
MK III	$3X10^{-12}$	$2.2X10^{-13}$
TGR	$2X10^{-12}$	Not Applicable

Table 7. Frequency Accuracy

4.7 Fractional Frequency Stability

Phase data was taken from the 5 MHz sine wave output at one second intervals for one hour and at one hour intervals over 64 days. These two data sets were used to calculate the Allan Deviation for sample periods of between 1 and 500,000 seconds with the results given in table 8. The MK III did not meet the TGR SCN-3 frequency stability specification at 100 and 1000 second.

Sample Interval, Seconds	1	10	100	1,000	10,000	Day
MK III Specification	$1X10^{-11}$	$1X10^{-11}$	$1X10^{-11}$	$2X10^{-11}$	$1X10^{-11}$	$1X10^{-12}$
TGR Specification	$1X10^{-10}$	None	$1.5X10^{-11}$	$1.0X10^{-11}$	$7.0X10^{-12}$	None
MK III Measured	$2X10^{-11}$	$8X10^{-12}$	***$3X10^{-11}$***	***$4X10^{-11}$***	$4X10^{-12}$	$4X10^{-13}$

Table 8. Allan Deviation (Bold type indicates out of spec.)

4.8 Conclusions

The Truetime MK III tested at NRL was found to meet most of the TGR time and frequency performance specifications. Its most glaring weakness comes from the fact that it is not a PPS receiver. The MK III does not meet the TGR frequency stability specification at 100 and 1000 seconds because of the combination of SA and the frequency steering algorithm used. During long term testing it was found that the MK III does not make the required GPS to UTC(USNO) time corrections as specified in GPS ICD-200. The Truetime MK III one pulse per second time output was found to be lagging GPS time by 76.1 ± 4.5 nanoseconds. The TGR specifications requires a 10 volt peak level for the one pulse per second signal whereas the MK III produced only a TTL pulse. The MK III phase noise floor was 6 dB above the TGR specification of -135 dBc.

While still not meeting all of the original TGR specifications the Truetime MK III should still make a good temporary replacement for the Loran-C receivers. The Truetime MK III may be only be considered a temporary solution due the fact that the DOD may require that all GPS receivers used be PPS-Y code capable. This means that DISA and the GPS JPO may have the requirement to produce a PPS-Y code GPS frequency and time receiver within the next few years.

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Appendix A

MEASUREMENT METHODS

A.1 TIME CALIBRATION

The time and frequency references used at the NRL Precise Clock Evaluation Facility (PCEF) are two Sigma Tau hydrogen masers. These masers produce both one pulse per second (1PPS) and a 5 MHz sine wave frequency reference signals that are synchronous with UTC(USNO). Th e traceable characterization of the reference 1PPS is accomplished using a "traveling clock" procedure augmented by continuous phase monitoring at NRL. First a measurement is made of the time epoch between NRL's Maser and a mobile HP-5071 Cesium Frequency Standard "traveling clock". Then this Cesium is transported to USNO and compared with their Master Clo ck and then returned to NRL again for a final comparison called clock closure. This procedure produces two difference equations. Simultaneous solution of these difference equations removes the "traveling clock" and produces the time difference between the NRL's Maser and the USNO's Master Clock.

To monitor the accumulated phase difference during periods between traveling clock trips, a continuous phase monitoring system is employed[3] (see diagram A.1). This system uses "common viewing" of a local television station (WTTG-TV5) carrier frequency. Both USNO and NRL monitor its signal with closure over a phone link. At each site the television carrier signal is mixed with a frequency derived from the in local primary frequency standard The difference frequency at each location is a 2250 Hz beat tone. The USNO beat tone is transferred to NRL via a dedicated phone line. At NRL, this beat tone is compared with a similarly derived beat tone to produce the phase difference between the USNO Master Clock and NRL's Maser. Combined with the traveling clock data, an estimate of the absolute time error between each location is maintained to less than two nanoseconds.

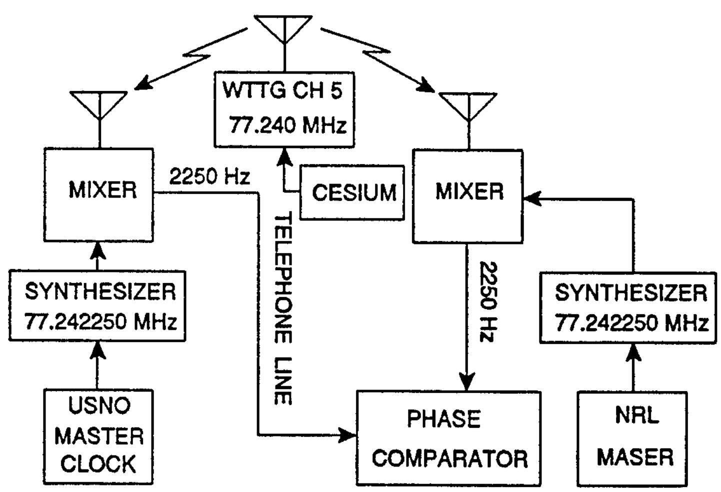

Diagram A.1. TIME CALIBRATION

A.2 ANALYSIS AND MEASUREMENTS

The Truetime's 1PPS was connected to the NRL 1PPS measurement system. This measurement system is capable of measuring sixteen input channels sequentially with 20 picoseconds single shot resolution at a sample interval of five minutes.

The receiver's 5 MHz output was connected to NRL's short and long term phase measurement systems, see figure A.2. The short term system is capable of measuring 12 inputs simultaneously, using dual mixer techniques, at a τ-interval of 20 seconds. It has a system noise floor of $6X10^{-12}$ over τ. The long term system is capable of measuring 48 inputs simultaneously. It too, uses dual mixer techniques, at a τ-interval of one hour. It has a system noise floor of $6X10^{-12}$ over τ. These systems together provided intermediate and long term fractional frequency data.

A.3 LIST OF TEST EQUIPMENT

The receiver's RF output was tested for phase noise and spurious signals using an extremely low noise test suite of equipment. Consisting of an HP 3562 Dynamic Signal Analyzer, a FemtoSeconds FSS 1000, and an HP 10 MHz crystal, the system measured the single sideband phase noise, $\mathcal{L}(f)$, from DC to 100 kHz. Spurious response was documented using an HP 8563 Spectrum Analyzer. All these systems taken together provided the necessary information about the receiver's precision time and frequency outputs. A complete list of the equipment used is shown below. A block diagram of the measurement system and how it connects to the Truetime MK III is shown in Diagram A.2.

IBM-AT 486 Computer used for serial data collection (Not shown)
FemtoSeconds Phase noise Detector FSS 1000
Hewlett Packard 10 MHz Quartz Oscillator
Hewlett Packard 3562 Dynamic Fast Fourier Transform Signal Analyzer (FFT)
Hewlett Packard 8753 Network Analyzer (Not Shown, Used To Measure Cable Delays)
Hewlett Packard Digital Oscilloscope 54111D
Hewlett Packard Spectrum Analyzer 8563A
Hewlett Packard Digital Synthesizer 3325
Time System Technology (TST), Inc. 6460 Clock
Sigma Tau Maser

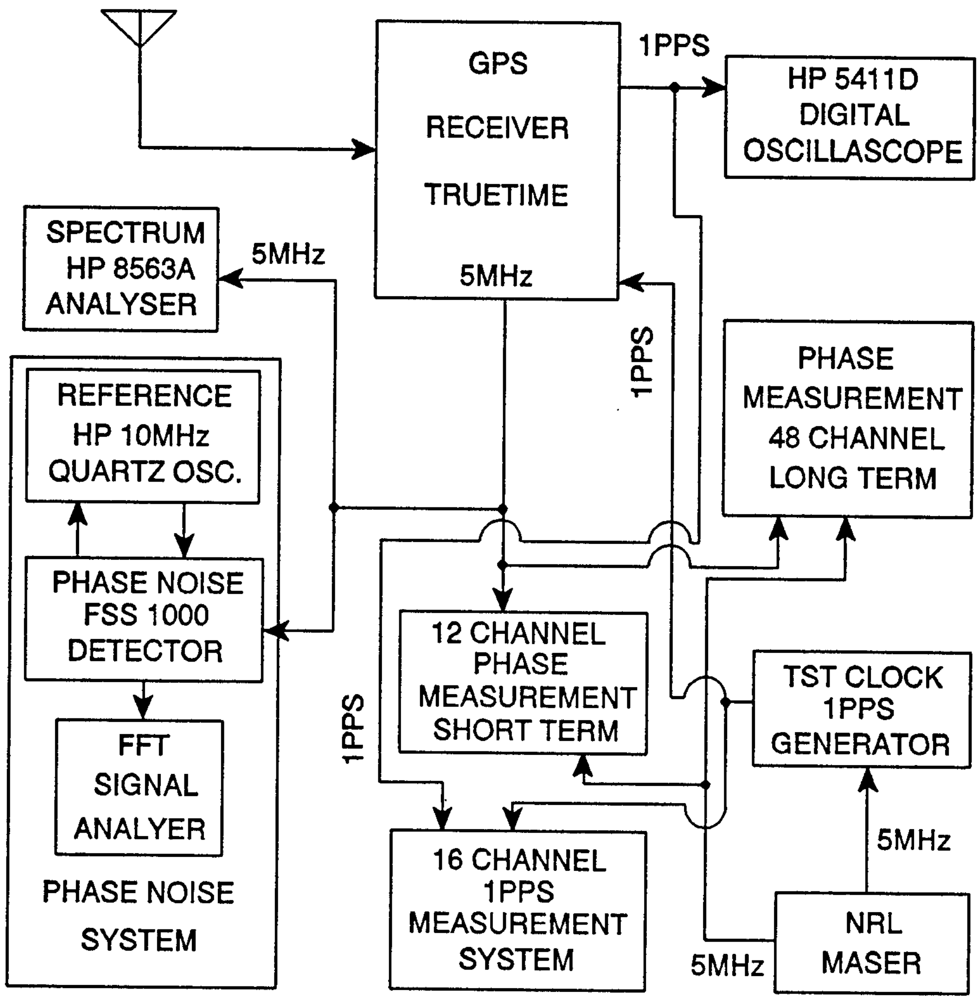

Diagram A.2. Precision clock evaluation facility.

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Appendix B

TGR SPECIFICATIONS (SCN-3)

The TGR specifications[4] are copied directly from the manual along with their section number as listed in the manual.

B.1 SELF SURVEY ACCURACY

3.2.1.1.5.2 Position Determination

The TGR shall be capable of determining the position of its antenna phase center in the World Geodetic System - 1984 (WGS-84) datum. Following operator command, or automatically, position determination shall be accomplished without requiring operator action. The TGR shall meet the frequency and time requirements when the position is determined by the TGR set or when a position is entered manually from a surveyed position accurate to within a 5 meters or less radial error. Manual entry of position data shall be entered as altitude, latitude and longitude and shall override any previous position computed or entered.

B.2 TIMING ACCURACY

3.2.1.1.1 1PPS Transfer Accuracy

Transfer accuracy relative to UTC (or GPS, if selected) Time shall be less than 100 ns RMS whenever one or more satellites are being tracked and the TGR antenna is positioned as described in paragraph 3.2.1.1.4.

B.3 ONE PULSE PER SECOND OUTPUT

3.2.2.1.2.2.2 Pulse Width

Pulse width shall be 20 microseconds ± 5 percent. The rise time shall be less than 20 nanoseconds and the fall time shall be less than one microsecond, as illustrated in MIL-STD-188-115

3.2.2.1.2.2.1 Output Voltage

The pulse amplitude shall be between 10 volts ± 10 percent and 0 volts ± 1 volt, as illustrated in MIL-STD-188-115.

B.4 SPURIOUS AND HARMONIC CONTENT

3.2.2.1. Time, Frequency, and Control Inputs and Outputs

a. Harmonic Distortion

As specified in MIL-STD-188-155, The harmonic distortion for the sine wave signal shall be at least 40 dB below the rated output level. The level of any signal component not a harmonic of the signal frequency shall be at least 60 dB below the rated output level.

B.5 PHASE NOISE MEASUREMENTS

3.2.2.1 Time, Frequency, and control Inputs and Outputs

b. Phase Noise

The following specification shall be met at all times after a 1 hour warm up period:

> - 87 dB @ 10 Hz from carrier
> - 120 dB @ 100 Hz from carrier
> - 135 dB @ 1 KHz from carrier

B.6 FREQUENCY ACCURACY

3.2.1.1.2 Frequency Accuracy

When the TGR is operating with outputs disciplined to GPS and is tracking satellites, the frequency accuracy shall be better than 1.0×10^{-11} RMS, when computed from a set of 9 frequency measurements, each measurement being averaged over one of 9 consecutive 10,000 second intervals.

B.7 FREQUENCY STABILITY

3.2.1.1.3 Frequency Stability

The frequency stability shall meet or exceed the following specifications:

1 sec (Allan var.) avg:	$1.0\text{X}10^{-10}$
100 sec (Allan var.) avg:	$1.5\text{X}10^{-11}$
1000 sec (Allan var.) avg:	$1.0\text{X}10^{-11}$
10,000 sec (Allan var.) avg:	$7.0\text{X}10^{-12}$ **
Frequency drift/day:	$5.0\text{X}10^{-10}$ (after loss of GPS tracking)

* * minimum of 10 pairs, non overlapping

Appendix C

TRUETIME MODEL GPS-DC-522 MK III RECEIVER SPECIFICATIONS

The model GPS-DC MK III (MK III) receiver specifications are copied directly or abstracted from two different TRUETIME manuals[5]. The layout of the front and rear panels of the TRUETIME receiver is shown in figure C.1.

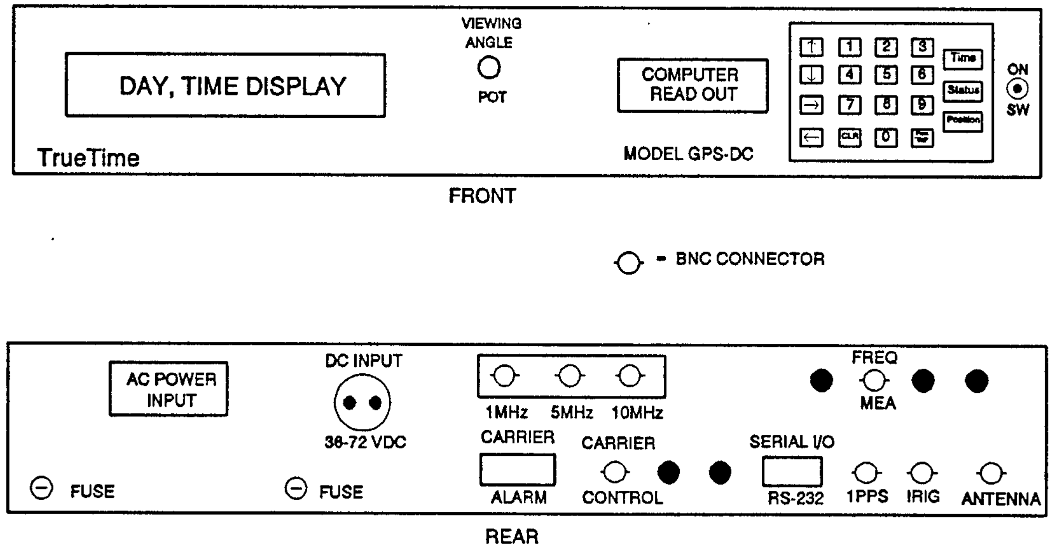

Figure C.1. TRUETIME receiver front and rear view.

C.1 SELF SURVEY ACCURACY

Position Accuracy: Latitude, longitude, altitude within 25 m (SEP) for a single fix referred to WGS84 when sequentially tracking four (4) or more satellites with a PDOP ≤ 6. If SA is being transmitted, the two dimensional RMS is 100 meters. The 24 hour averaged position accuracy is < 10 m.

C.2 TIMING ACCURACY

GPS Time ± 150 ns.
UTC(USNO) ± 150 ns.

Both specifications are valid when the antenna's geodetic position is known within 25 m and one satellite is being tracked. The timing accuracy to UTC(USNO) is ±300 ns during the

enforcement of selective availability.

C.3 ONE PULSE PER SECOND OUTPUT

On time edge: positive rising.
Amplitude: TTL compatible, $\geq$ 2.5VDC into 50 ohms.
Drive: 50 ohm.
Connector: Rear panel BNC.

C.4 SPURIOUS AND HARMONIC CONTENT

Harmonic distortion: -50 dBc from 5 MHz sine wave output.
Spurious not specified

C.5 PHASE NOISE MEASUREMENTS

None specified.

C.6 FREQUENCY ACCURACY

Frequency Output Accuracy:
Less than 3×10^{-12}

C.7 FREQUENCY STABILITY

Frequency/Timing stability when tracking satellites:
Allan Deviation

1×10^{-11}	@	1 sec
1×10^{-11}	@	10 sec
1×10^{-11}	@	100 sec
2×10^{-11}	@	1000 sec
1×10^{-11}	@	10000 sec
1×10^{-12}	@	100000 sec

Oscillator Temperature Coefficient:
$<1 \times 10^{-10}/°C$ in holdover mode.

Appendix D

DESCRIPTION OF TEST RESULTS

D.1 TEST DESCRIPTION

All test were performed with the receiver in the auto/time transfer mode and using live satellites. Testing began on the first version of the Truetime MK III in September 1994 and testing of the finial fielded unit was completed in January 1996.

D.1.1 Position

The antenna was installed on the roof of NRL building 53 two meters (m) above the NRL benchmark. The Defense Mapping Agency (DMA) calibrated height of the NRL benchmark is -18.15 m World Geodetic Survey, 1984 (WGS-84). The corrected height of the TRUETIME antenna is -16.15 m WGS-84. The antenna has a low noise pre-amplified L1 band antenna section and a built in down converter. The receiver was turned on and allowed to warm up for 12 hours. The approximate longitude and latitude of the receiver's antenna was loaded into the receiver, and the receiver was then allowed to self-survey the antenna location for 24 hours. The MK III then stores this average self-survey in non-volatile memory and automatically switches to TIME mode. Position coordinate errors are listed in table D.1. To establish an upper bound on timing errors due to position uncertainty, the Root-Squares-Summed (RSS) was computed to be 4.2 meters. The nominal timing error due to these position errors would be about 14 nanoseconds (ns). This error is small when compared to the effect of SA on the GPS derived time signal.

Dimension	Receiver software position WGS-84	True antenna position WGS-84	Error
height	-15 (m)	-16.15 m	-1.15±0.5 m
latitude	N 38° 49.2367′	N 38° 49.2363′	S 0.74±1.5 m
longitude	W 77° 01.465′	W 77° 01.4676′	W 3.75 ±1.2 m
Error RSS			4.2 ±1.98 m

Table D.1. Position Measurements

D.1.2 Time Accuracy

A detailed calibration of all MK III timing system errors were completed. The MK III antenna cable delay was measured to be 560 nanoseconds. The delay from the receiver's time output to the NRL measurement system was measured to be 160 nanoseconds. The MK III manual states that the combined receiver, antenna and down converter delay should be entered as -200 nanoseconds. This brings the total MK III system delay to be +360 nanoseconds. The procedure for how to compute the total MK III receiver delay was verified during several telephone conversations with the manufacturer (Truetime Inc.). The MK III 1PPS time signal, when averaged over time intervals of 24 hours, and covering a period of three months was found to be lagging UTC(USNO) time by 76.1 ±4.5 nanoseconds as shown in figure D.1.

During long term testing it was found that the MK III does makes the integer leap second correction to UTC but not the required fractional second of GPS to UTC(USNO) time corrections as specified in GPS ICD-200. GPS time is typically maintained to within ±30 nanoseconds of UTC(USNO) time, and GPS time is only required to be within ±1 microsecond at present. The problem was verified by Truetime and will be fixed for future units. Thus the measured bias is composed of receiver system bias and the uncorrected UTC(USNO) offset to GPS time. The average UTC(USNO) GPS bias for the test period was 0 nanoseconds leaving a net bias of 76.1 ±4.5 nanoseconds due to the receiver.

The navigation message provides information for determining UTC(USNO) time ($T_{UTC(USNO)}$) from GPS time (T_{GPS}). GPS time[6] differs from UTC(USNO) time by an integer number of seconds because of leap second adjustments to UTC(USNO) time due to changes in the rotation of the earth. GPS time also differs from UTC(USNO) by a small fraction of a second due to time scale differences. Both corrections must be applied. The equation has an approximate general form of:

$$T_{UTC(USNO)} = T_{GPS} - \text{correction to UTC(USNO)}$$

or

$$T_{UTC(USNO)} = T_{GPS} - (\Delta T_{LS} + A_0 + A_1 T)$$

where ΔT_{LS}, A_0, and A_1 terms, are the leap second correction, correction to GPS time one second epoch, and the run off rate of GPS time respectively. T is compose of a number of terms which represents the accumulated time since the UTC(USNO) epoch time, and the exact details of the above equation can be found in GPS ICD-200.

D.1.3 One Pulse Per Second Characterization

The output 1PPS is a TTL-type logic level compatible, positive-going, 20 microsecond wide pulse when driving a 50 ohm load impedance. The full pulse is shown in figure D.2 with an amplitude of 3.4 volts with a slight overshoot. Note the output level is not 10 volts peak pulse as requested in the TGR specifications. Figure D.3 shows that the MK III 1PPS timing signal has a very fast rise time of 1 nanosecond. The fall time is shown in figure D.4, also 1 nanosecond. Figure D.5 shows unwanted EMI leakage from the IRIG circuitry that bleeds into the 1PPS output.

D.1.4 Spurious And Harmonic Content

The 5 MHz RF output (see figure C.1) of the receiver was checked for spurious and harmonic signals. Figure D.6 shows the 5 MHz primary output at a level of +13.1 dBm along with its integer harmonics out to 50 MHz. The amplitude of the receiver's harmonic content is much less than required by the TGR specification.

Figure D.7 is a plot of the frequency spectrum from 100 kHz to 4.95 MHz using a quarter-wave trapping stub to attenuate the main 5 MHz signal. This method increases the dynamic range of the analyzer and pulls small signals out of the analyzer system noise. Note the crosstalk into the 5 MHz output coming from the 1 MHz frequency output displayed in this plot. Also note the numerous frequency components approaching the fundamental. These are believed to be Amplitude Modulation artifacts from a 78 kHz signal detected in the single sideband phase noise plots shown later in this paper. All observed discrete frequency components were well below the manufacturer's and TGR specifications.

Figure D.8 is the broadband spectral plot also using the quarter wave trap. Note the group of frequencies around the 30 MHz region. They have no obvious source but are well below the TGR and the Truetime specifications.

D.1.5 Phase Noise Measurements

Figures D.9 through D.12 are made from the NRL single sideband phase noise measurement system. They cover a span from 10 Hz to 100 kHz. All figures are in units of dB below carrier, dBc or $L(f)$. Figure D.9 is a very narrow band look at the carrier. It show some leakage of the 1PPS signal into the frequency outputs. Figure D.10 is free of any unusual signals, even around the 60 Hz area where power line interference usually occurs. Figure D.11 shows the signal out to 10 kHz. The 1 kHz signal seen in figure D.11 is believed to be crosstalk from the IRIG circuitry. Figure D.12 shows a strong 78 kHz frequency component. All observed signals are well below the TGR and Truetime specification. The overall phase noise floor of the Truetime MK III was 6 dB above the TGR specification of -135 dBc.

D.1.6 Frequency Accuracy

The absolute frequency offset of the 5 MHz sine wave output with respect to USNO was measured and the data is shown in figure D.13. The MK III frequency offset measurement of 2.2 E-13 is the result of data averaged from (10) 3 hour averaging periods per the TGR SCN-3 specifications.

D.1.7 Fractional Frequency Stability

Phase data was taken from the 5 MHz sine wave output at one second intervals for one hour and at one hour intervals over 64 days. These two data sets were used to calculate the Allan Deviation for sample periods of between 1 and 500,000 seconds. Figure D.14 is an Allan Deviation, $\sigma_y(\tau)$, plot of the frequency data. The slight rise in the Allan Deviation at the one second sample intervals was a result of the 1PPS leakage referred to in section D.1.5. The peak occurring at 300 seconds is due to the SA and the servo loop steering in the MK III. The Allan Deviation of figure D.14 does not satisfies the TGR specifications at 100 and 1000 seconds.

D.1.8 Conclusions

The Truetime MK III tested at NRL was found to meet most of the TGR time and frequency performance specifications. Its most glaring weakness comes from the fact that it is not a PPS receiver. The MK III does not meet the TGR frequency stability specification at 100 and 1000 seconds because of the combination of SA and the frequency steering algorithm used.

The navigation message provides information for determining UTC(USNO) time from GPS time(see D.1.2). During long term testing it was found that the MK III does not make the required (A_0 + A_1 term) UTC(USNO) to GPS time corrections as specified in GPS ICD-200. The Truetime MK III one pulse per second time output was also also found to be lagging GPS time by 76.1 ± 4.5 nanoseconds. The TGR specifies a 10 volts peak level for the one pulse per second signal whereas the MK III produced only a TTL pulse. The MK III phase noise floor was 6 dB above the TGR specification of -135 dBc.

While still not meeting all of the original TGR specifications the Truetime MK III should still make a good temporary replacement for the Loran-C receivers. The Truetime MK III may be only be considered a temporary solution due the fact that the DOD may require that all GPS receivers used be PPS-Y code capable. This means that DISA and the GPS JPO may have the requirement to produce a PPS-Y code GPS frequency and time receiver within the next few years.

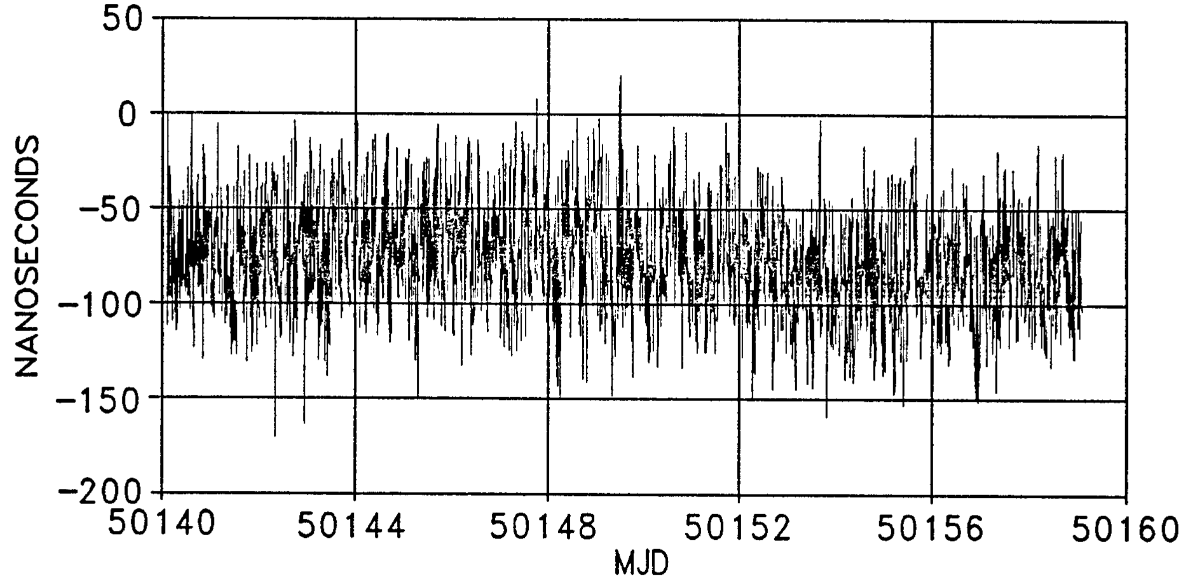

Figure D.1. True Time MKIII receiver time error VS USNO(MC2).

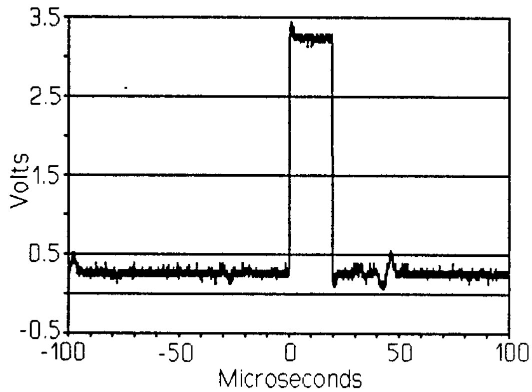

Figure D.2. 1PPS output.

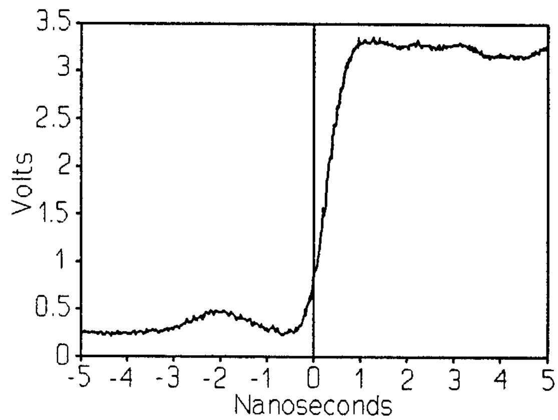

Figure D.3. Rise time of 1PPS.

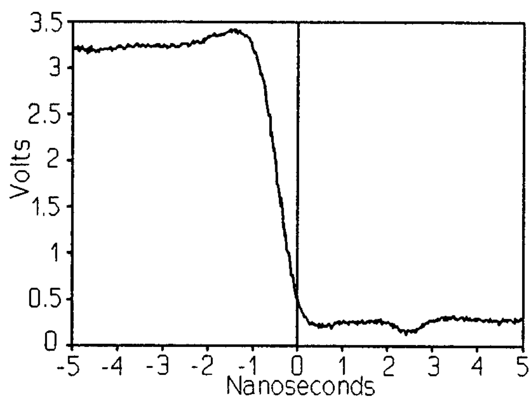

Figure D.4. Fall time of 1PPS.

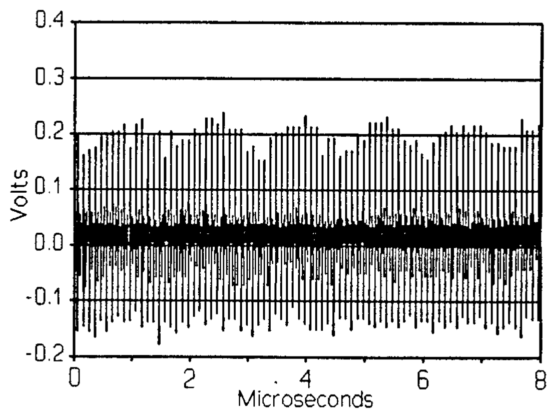

Figure D.5. Noise on 1PPS

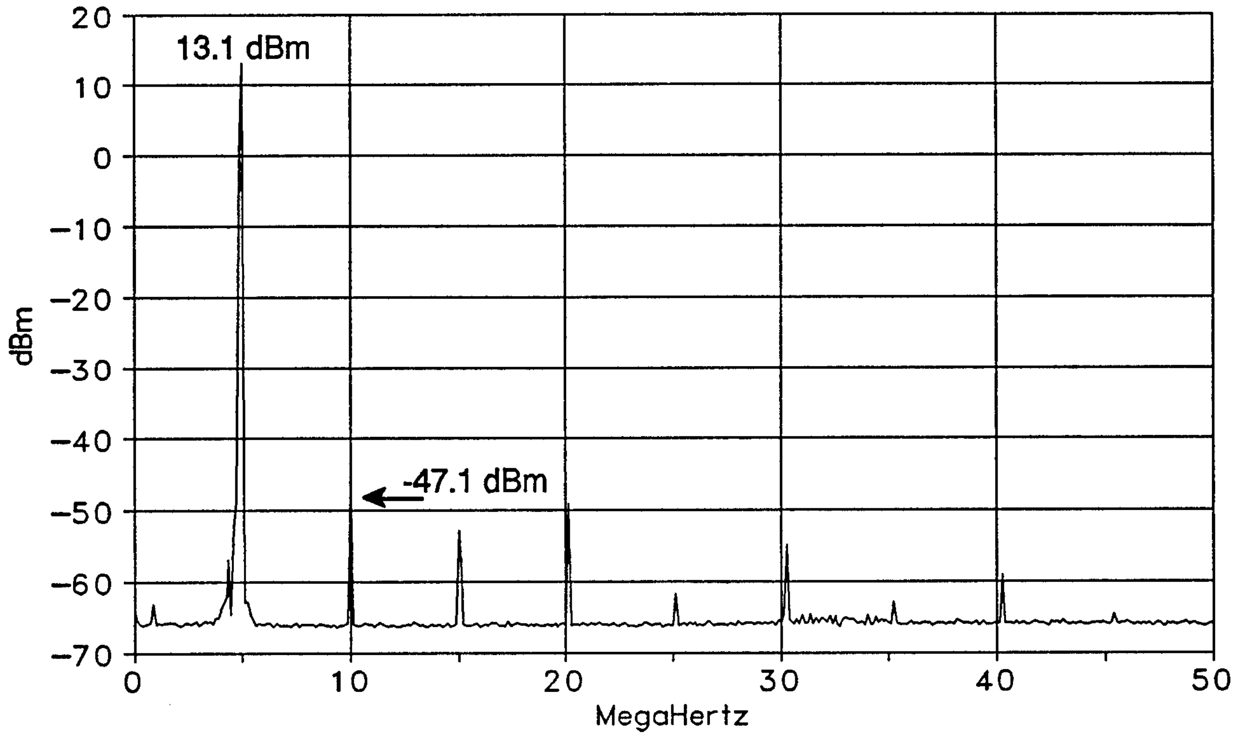

Figure D.6. 5MHz output with harmonics out to 50 MHz.

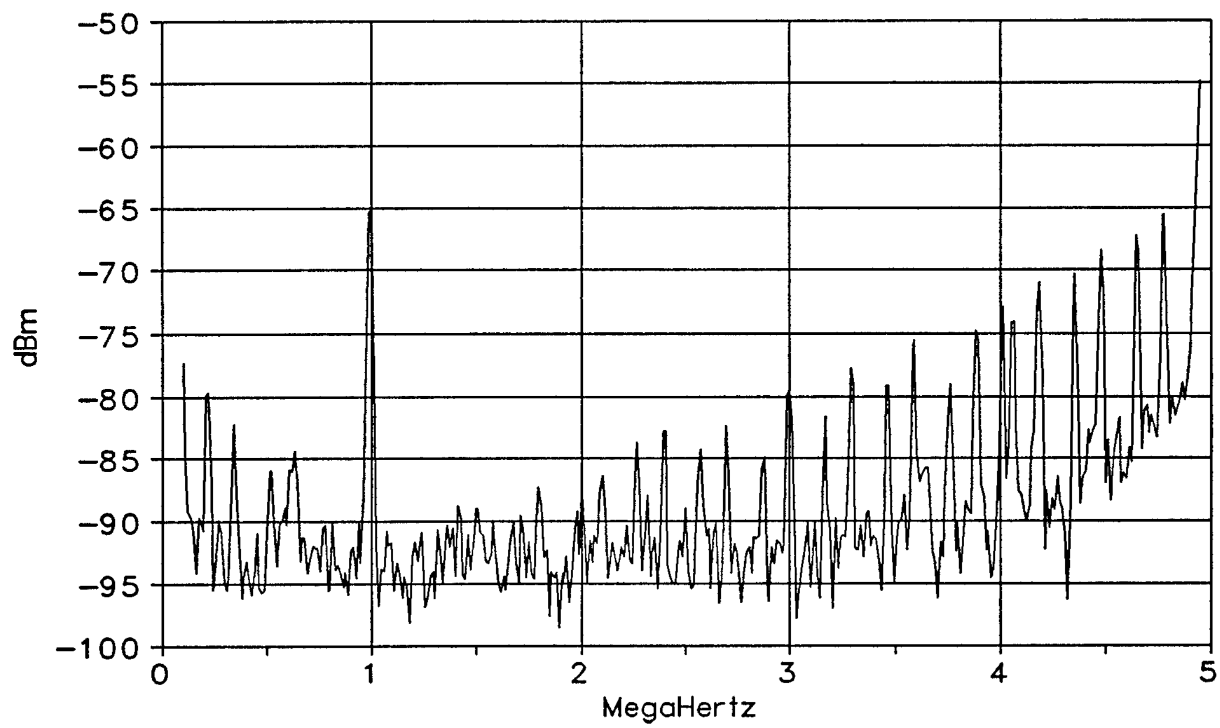

Figure D.7. 5 MHz output from 100 kHz to 4.95 MHz. 1/4 wave trap at 5 MHz.

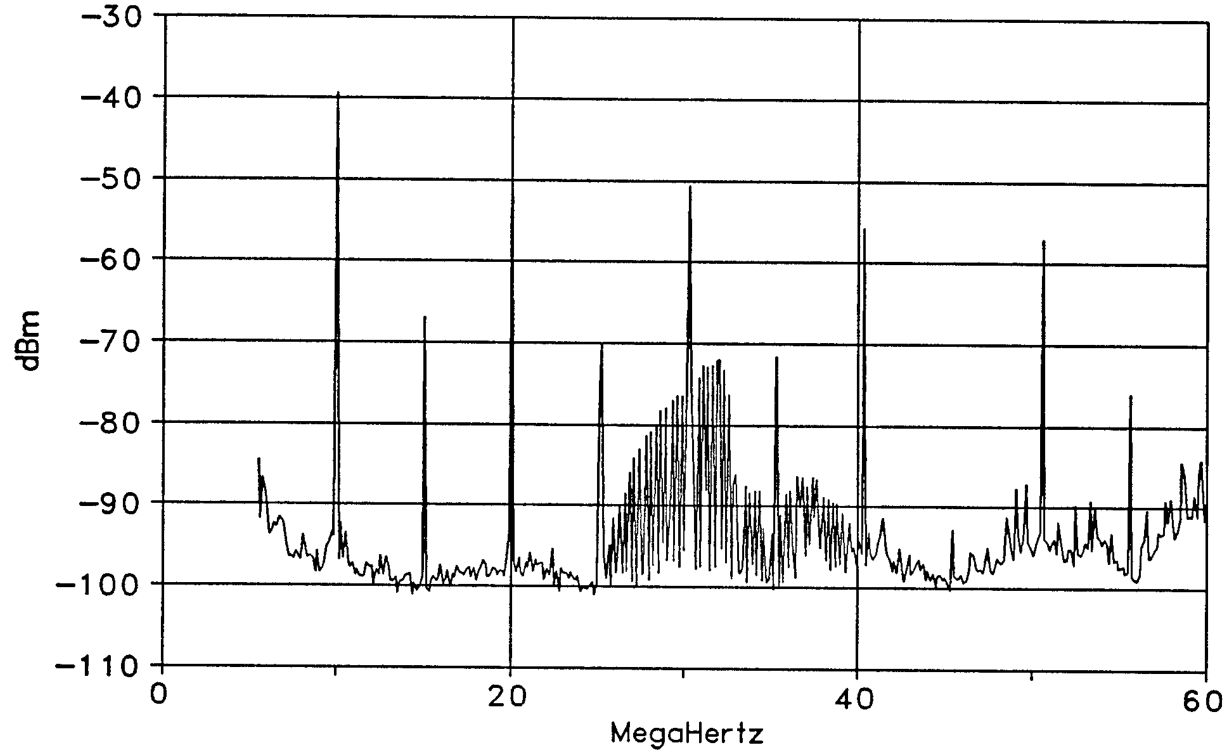

Figure D.8. 5MHz output from 5 to 50 MHz with a 1/4 wave trap at 5 MHz.

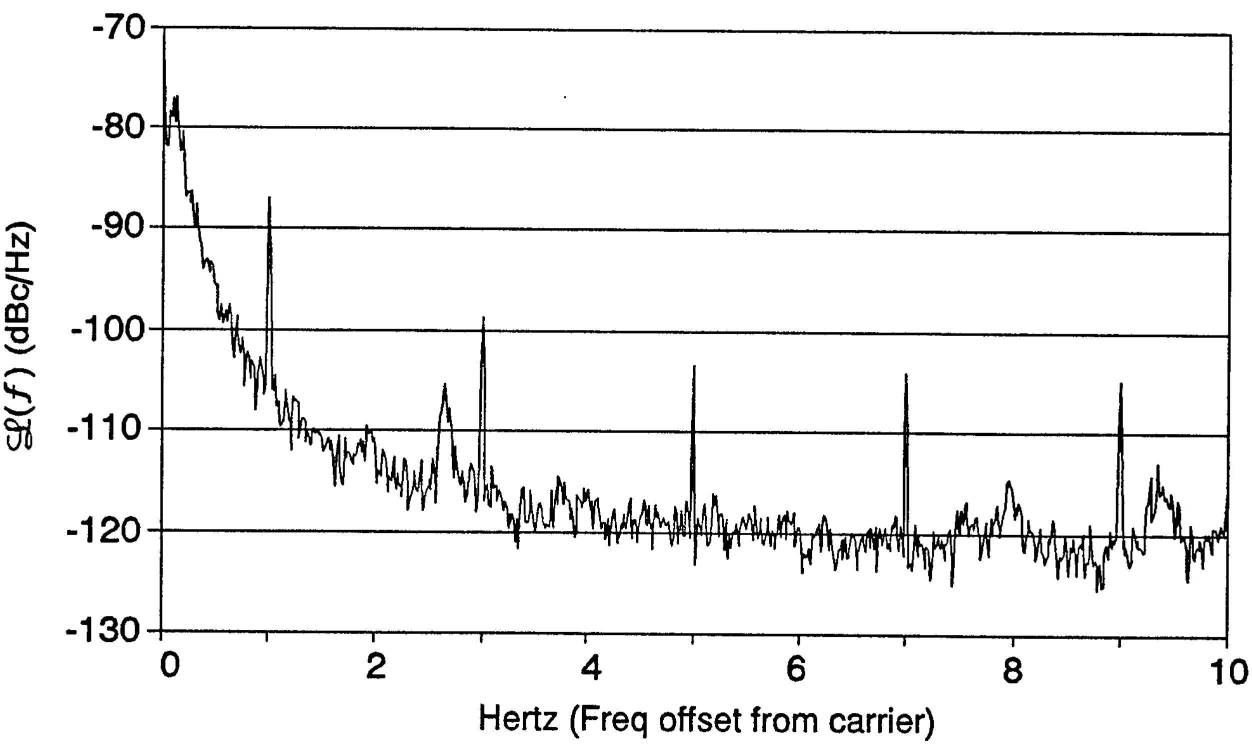

Figure D.9. Phase noise to 10 Hz from the 5 MHz output.

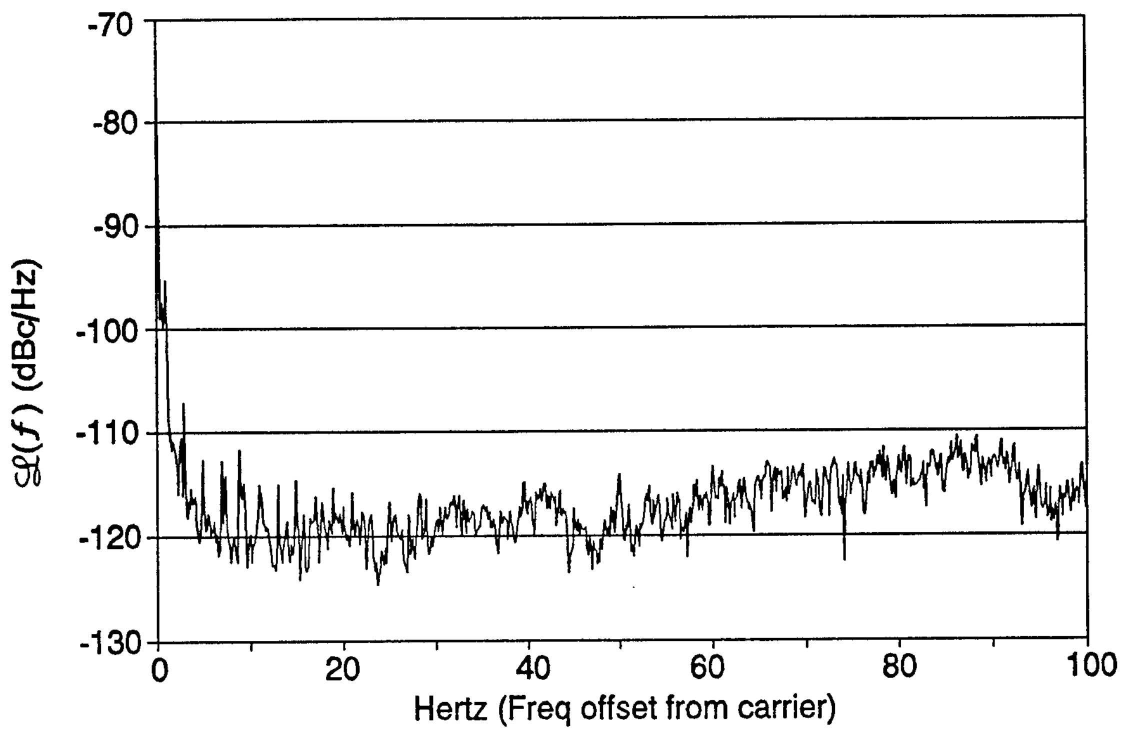

Figure D10. Phase noise to 100 Hz from the 5 MHz output.

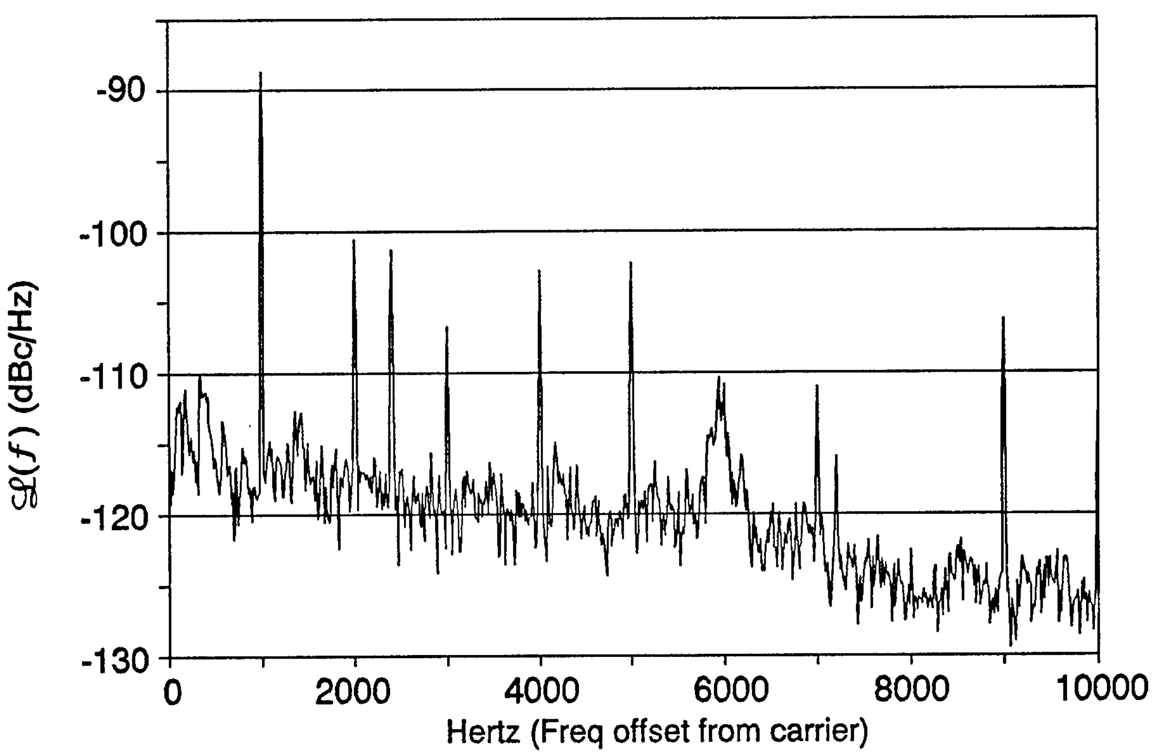

Figure D.11. Phase noise to 10 kHz from the 5 MHz output.

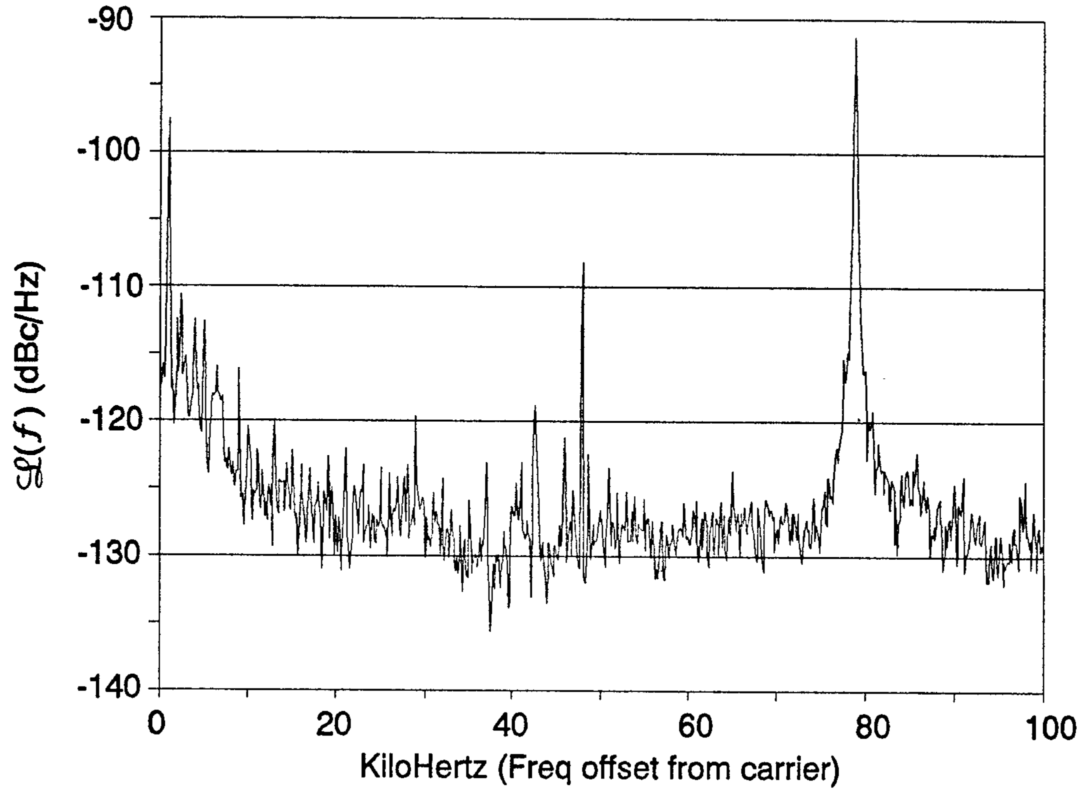

Figure D.12. Phase noise to 100 kHz from the 5 MHz output.

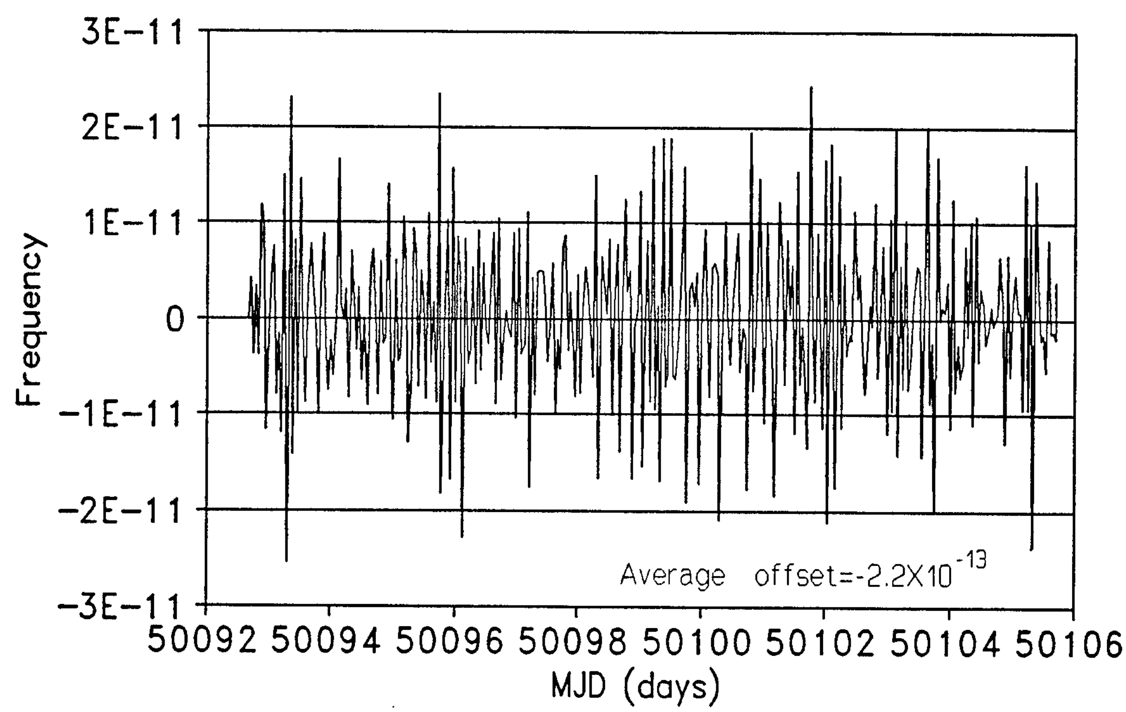

Figure D.13. Frequency data of the receiver's 5 MHz output.

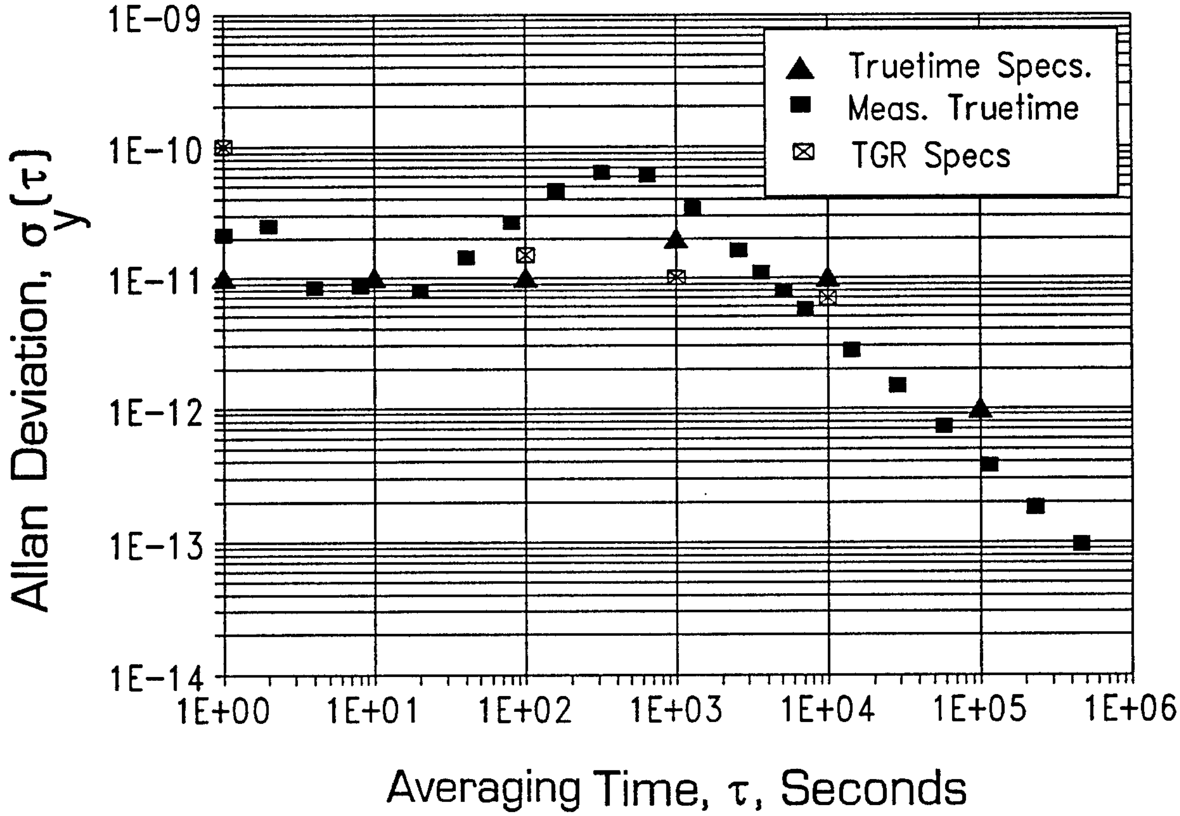

Figure D.14. Allan Deviation plot of the frequency data and specifications.

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